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1995-1996 TECHNICAL PROGRESS REPORT

Numerical MHD Studies of Accretion Disks
Grant NAG 5 3058

PI: John F Hawley, University of Virginia
CoI: Steven A. Balbus, University of Virginia

Work completed in the past year

One of the most important goals in the study of astrophysical disk systems has been to understand the angular momentum transport mechanism. A principle aim of this project has been to study and elucidate the development of the magnetorotational instability (Balbus & Hawley 1991, ApJ, 376, 214) in accretion disks systems, and the properties of the resulting angular momentum transport. As a result of work supported by this grant, we believe that matters are now at a stage where the underlying mechanism of angular momentum transport is not in doubt: turbulence in accretion disks is MHD turbulence. The questions that remain relate to how this turbulence fits in to global disk models, and the level of turbulence expected under various physical preconditions. These are hard questions, of course, but the progress of recent years has been remarkable, and we are optimistic that much of the same lies ahead. These are truly the best of times to be doing accretion disk theory!

We have completed and published a study [3] demonstrating that even random configurations of weak (subthermal) magnetic fields in accretion disks lead directly to magnetohydrodynamic (MHD) turbulence and astrophysically significant angular momentum transport. The power spectrum of the turbulence has been studied and characterized. (It is Kolmogorov-like.) Both the turbulence and the magnetic field are mutually self-sustaining. Hence, in disks, the magnetorotational instability is a dynamo. A related study [1] examined the evolution of weak field configurations in more realistic vertically-stratified local disk domains. Again, self-sustaining MHD turbulence rapidly develops, leading to outward angular momentum transport at a rate of $\alpha \sim 0.01$, in the conventional α-disk parlance, where the stress tensor is proportional to the pressure, i.e., αP. Vertical stratification leads to vertical transport of magnetic fields, but not at a level so rapid that is quenches the instability. The result is a disk with a weakly magnetized core surrounded by regions of stronger magnetic field, suggestive of a magnetized disk corona.

Another major project carried out during the past year investigated purely hydrodynamic mechanisms for angular momentum transport. In particular, we sought to compare the properties of the turbulence that may (or may not!) be present in the following types of flows: convectively unstable disks, Rayleigh unstable disks, high Reynolds number shear layers, and Keplerian disks. The results of our numerical studies [2,4,5,6] imply that *no* hydrodynamical turbulence mechanism, convective or otherwise, will produce enhanced transport in a Keplerian disk. Indeed, in numerical simulations, convection transports angular momentum *inward*, from regions of greater to lesser specific angular momentum [2]. Even in a simulation in which turbulence was directly excited in a Keplerian disk by external forcing [10], and the rms velocity fluctuations grew with time, the Reynolds stress fluctuated about zero. Moreover, we have shown that accretion disks are both linearly and nonlinearly *stable* to the large Reynolds number instabilities that beset ordinary shear flow [4]. We have been able to reproduce easily nonlinear high Reynolds number instabilities (and enhanced transport) in pure shear flows, but not in flows with differential rotation. The one exception to the last statement is that disks with a constant specific angular momentum profile were found to be nonlinearly unstable (a new result); in fact we were able to show that the local dynamics of such disks are equivalent to those of a shear layer. Such disks are not stabilized by epicyclic motions. The importance of these constant angular momentum disks lies not with their direct astrophysical applicability, but with the clarity with which they illustrate an important principle: the key stabilizing feature is the presence of Coriolis forces, which in a Keplerian disk are never negligible. Our studies, which combine both numerical and analytic arguments, have far reaching consequences for our understanding of how turbulence works in accretion disks: enhanced turbulent transport must be magnetic.

In addition to the cited publications, these results were presented in invited talks [7,8] by the PI and/or the CoI at the 1996 Joint meeting of the APS and AAPT, 2-5 May, 1996, Indianapolis, Indiana, and at the IAU Colloquium 163: Workshop on "Accretion Phenomena and Related Outflows," July 15-19, 1996, Port Douglas, Australia, [9,10].

Ongoing work

A goal in this research project has been to develop a version of the 3D MHD code for cylindrical coordinates as the first step toward computing global disk simulations. Preliminary testing of a such a global three-dimensional MHD code has begun. The development of the global hydrodynamic Papaloizou-Pringle instability has been used as a test problem; phenomena seen in earlier simulations have been reproduced (e.g., Hawley 1991, ApJ, 381, 496). Development of the MHD portions of this code are proceeding; test comparisons will be made against the local MHD instability simulations already performed. We anticipate that this stage will soon be completed, and that several projects involving global simulations will be carried out during the next year.

Because of the relative ease of simulating hydrodynamical turbulence in shear layers, we will be able to follow-up on an important earlier finding: shear layer turbulence does not appear to amplify magnetic fields [10]. This is in stark contrast to the MHD instability in disks, which certainly does amplify fields, and runs counter to a prevailing common wisdom. In preliminary shear layer studies, after an initial period of growth, the magnetic field decays to zero. Nothing of the kind is observed in 3D accretion disks studies, although in 2D studies such decay *is* seen. Of course, there can be no dynamo activity in less than three dimensions, and the qualitative similarity in the behaviors of shear layers and 2D MHD simulations may be telling us something important. We will investigate this much further, and compare (at a number of different resolutions) the behaviors of shear layers, disks, and directly stirred fluids.

We shall also be continuing our investigation into specific saturation mechanisms for the MHD instability. Simulations to date point to the importance of the small-scale *magnetic Prandtl number* (the ratio of the microscopic viscosity to resistivity). Large viscous diffusion relative to resistive diffusion have been found to lead to proportionately larger final mean

B-field values. This seems to be due to the large viscous stresses preventing fluid elements from reconnecting field lines when the resistive length scale is subviscous. In simulations, the viscosity and resistivity have diffusive lengths set by the size of the grid zones. Of necessity, these must be considerably larger than those appropriate to real disks, and we are well aware of our dynamic range limitations. Nevertheless, by adding these quantities explicitly to the code, we can investigate something of their *relative* importance. It is potentially very important: the Prandtl number is likely to be extremely temperature-sensitive. (In a Coulomb gas the ratio goes as the fourth power of the temperature.) If the Prandtl ratio has strong role in regulating the effective α parameter for the disk, it needs to be understood. We will be carrying out such simulations over the course of the upcoming year.

1996 Publications

[1] Stone, J.M., Hawley, J.F., Gammie, C.F., & Balbus, S.A. 1996, "Three-Dimensional Magnetohydrodynamical Simulations of vertically stratified Accretion Disks," ApJ, 463, 656-673.

[2] Stone, J.M. & Balbus, S.A. 1996, "Angular Momentum Transport in Accretion Disks via Convection," ApJ, 464, 364-372.

[3] Hawley, J.F., Gammie, C.F., & Balbus, S.A. 1996, "Local Three Dimensional Simulations of an Accretion Disk Dynamo," ApJ, 464, 690-703.

[4] Balbus, S.A., Hawley, J.F., Stone, J.M. 1996, " Nonlinear Stability, Hydrodynamical Turbulence, and Transport in Disks," ApJ, **467**, 76-86.

[5] Balbus, S.A. and Hawley, J.F. 1996, "Origin of Turbulent Viscosity," *Basic Physics of Accretion Disks*, S. Kato et al (eds), in press.

[6] Hawley, J.F. and Balbus, S.A. 1996, "Numerical Simulations of Accretion Disks: Sources of Anomalous Viscosity," *Basic Physics of Accretion Disks*, S. Kato et al (eds), in press.

[7] Hawley, J.F. 1996, "Three Dimensional MHD Simulations of Accretion Disks," *Bull. Amer. Phys. Soc.*, 41, 992-993.

[8] Balbus, S.A. 1996, "The Stability of Magnetized Rotating Plasmas," *Bull. Amer. Phys. Soc.*, 41, 993.

[9] Balbus, S.A. and Hawley, J.F. 1996, "Instability, Turbulence, and Enhanced Transport in Accretion Disks," *Accretion Phenomena and Related Outflows*, D. Wickramasinghe, L. Ferrario, & G. Bicknell (eds), in press.

[10] Hawley, J.F. and Balbus, S.A. 1996, "Three-Dimensional Simulations of Accretion Disks," *Accretion Phenomena and Related Outflows*, D. Wickramasinghe, L. Ferrario, & G. Bicknell (eds), in press.